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EFFECT OF TEMPERATURE OF THE SPECIFIC RATE OF BURNING
OF SMOKELESS POWDER

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Abstract

A new equation for the specific rate of burning as a function of
the temperature is developed. Constants in the equation are deter-
mined directly from the experimental data.

Former theories[1,2] concerning the effect of temperature
on the specific rate of burning have assumed that it is
necessary to evaporate the volatiles from the powder before
it will burn. Since the critical pressure of both water
and ethyl alcohol are low compared to the pressures developed
in a gun, almost immediately after ignition the pressure of
the powder gas will be above the critical pressure* of these
substances and no change of phase will occur. Hence to cause
the powder to burn it is necessary only to raise it to the
ignition temperature.[3]

[1] L. S. Dederick - Specific Rate of Burning of Smokeless Powder.
[2] W. H. Tschappat - Ordnance and Gunnery. p. 116.
[3] Crow and Grimshaw - The Combustion of Colloidal Propellants. Phil.
    Trans. Roy. Soc. Vol. 230.

*	Crit. Press.	Crit Temp.
Water	194.6 atmos.	365° C
Alcohol	62.7	230° C

If we consider a layer of powder of thickness, dr, the time, dt, required for sufficient heat to ignite the powder, to be transferred from the hot gases, is directly proportional to the quantity of heat necessary to raise it to the ignition temperature and inversely proportional to the rate of transfer. The amount of heat necessary to raise a layer of thickness, dr, to the ignition temperature is directly proportional to the product of the specific heat, s, of the solid powder and the temperature range, T_1-T_0, through which it is raised. As a rough approximation, the rate of transfer of heat energy from the hot gases to the powder is proportional to n', the specific energy of the powder. Therefore at a constant pressure, p, we may write

$$dt \propto \frac{s(T_1-T_0)dr}{n'} .$$

If the rate of burning is proportional to p^e then

$$\frac{dr}{dt} = \frac{cn'}{s(T_1-T_0)}p^e = K'p^e \quad \text{(definition of K')} \tag{1}$$

in which c is a proportionality factor. If s, the specific heat of the solid powder, is assumed constant it may be combined with the proportionality factor c.

If

$$\frac{c}{s} = a \qquad \text{then}$$

$$K' = \frac{an'}{T_1-T_0} . \tag{2}$$

K' is the rate of combustion in inches per second measured perpendicular to the burning surface, where the powder is burning in its own gas at a pressure of 1 lb. per sq.in T_1 is the ignition temperature of the powder and T_0 is the initial powder temperature. The standard firing temperature is 21.1° C so T_0 may be replaced by the expression $(21.1+\Delta T)$ where ΔT is the difference between T_0 and 21.1°C. The denominator of (1) becomes $T_1-21.1 - \Delta T$ and if we replace

T_1-21.1 by b, equation (1) becomes

$$K' = \frac{an'}{b-\Delta T}.$$ (3)

If a and b are constants and n' is approximately constant
for each type of powder, then K' is a function of the powder
temperature only. If K' may be represented by equation (3),
it is obviously desirable to determine a and b from ex-
perimental data. This can best be accomplished by using
the method of least squares. In order to have the expression
for K' in a more convenient form, we make use of the sub-
stitutions

$$y = \frac{n'}{K'} \qquad a' = -1/a \qquad b' = \frac{b}{a}$$

equation (3) becomes

$$y = a'\Delta T + b'$$ (4)

a' and b' can be calculated by the method of least squares
from the available temperature firings and from these a and
b are determined. The specific energy, n', is computed from
the composition of the powder. K' is calcubated directly from
the firing data with the aid of the equation from Bennett.[1]

$$q = q_o \frac{K'}{R} d^{1/2} \left(\frac{n'}{n'_o}\right)^{1/6}$$

q, the quickness is determined from the tables since the
density of loading and the maximum pressure are known. R, d
and n'_o are as defined by Bennett. We assume q_o is unity,
since we are interested in only the change in K' for a
variation in the initial temperature of the powders and q_o
is not a function of the temperature.

Table I is a summary of the experimental data used in
calculating a and b. Table II shows the values obtained
for a and b and their probable errors for the two types of
powder and also for the case in which all the available
data was used without regard to the kind of powder.

[1] A.A. Bennett - Tables for Interior Ballistics.

Table III is a comparison between the computed and experimental values of ΔV/ΔT for various guns. For each of the several gun, projectile and powder combinations, least square straight lines showing muzzle velocity as a function of the temperature are given in a report by Feltman.[1] The slopes of these lines determine the experimental values of ΔV/ΔT. The computed values of ΔV/ΔT were obtained by calculating ΔV for a suitable interval of T from Bennett's Interior Ballistic Tables with the aid of equation (3).

Ignition Temperature

It should be noted that b is really T_1 - 21.1 so that b + 21.1 is the ignition temperature of the powder. The value of b (415) as obtained by the method of least squares from the firing records indicates that the ignition temperature is 436°C. This is much higher than the accepted value 180°C.* The accepted value of T_1 is obtained by a relatively slow heating of the powder and it is probable that T_1 is greater under firing conditions than under the conditions of slow heating.

This investigation was suggested by Mr. R. H. Kent and I am greatly indebted to him for suggestions and criticisms.

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[1] Samuel Feltman - First Partial Report on the Effect of Temperature of Powder on Velocity and Pressure. O.P. #4858. 1-Z-14.
* W. H. Tschappat - Ordnance and Gunnery, page 117.

TABLE I

Powder	155 mm Howitzer Lot 773, n' = 117x10⁴		4.7" Gun* n'= 120x10⁴	75 mm 1897 Gun Lot 1164-S			n' = 119x10⁴ ft.lb/lb
Proj. Wt.	95	95	45	11.72	15.96	13.50	11.72
Charge, lb.	3.59	5.16	7.42	.61	1.51	1.61	1.32
Density of Loading	.240	.342	.820	.204	.508	.541	.441
Temperature °F	46°	46°	43°	50°	50°	50°	50°
P_{max} lb/in²	8666	14,766	28,217	8670	32,280	34,950	22,820
q	.0778	.0852	.0500	.0893	.0991	.0977	.0899
K'	.00364	.00397	.00401	.00450	.00425	.00454	.00449
Temperature °F	59°	59°	59°	70°	70°	70°	70°
P_{max}	8733	15,650	28,383	8295	34,275	34,495	23,710
q	.0782	.0891	.0501	.0858	.1033	.0969	.0925
K'	.00366	.00416	.00403	.00433	.00443	.00450	.00462
Temperature °F	70°	70°	70°	90°	90°	90°	90°
P_{max}	9083	15,533	29,867	8340	34,320	37,260	24,410
q	.0810	.0886	.0520	.0862	.1034	.1022	.0945
K'	.00379	.00414	.00417	.00435	.00444	.00475	.00472
Temperature °F	84°	84°	83°	110°	110°	110°	110°
P_{max}	9383	16,050	30,133	8330	37,880	39,970	24,610
q	.0833	.0909	.0523	.0861	.1106	.1071	.0950
K'	.00390	.00424	.00423	.00434	.00475	.00498	.00475
Temperature °F				135°	135°	135°	135°
P_{max}				.0938	.1150	.1088	.0978
K'				.00473	.00493	.00505	.00488

* Pressures for 155 mm Howitzer and 4.7" Gun are an average of 3 rounds.

TABLE I (CONTINUED)

Powder	75 mm 1897 Gun FNH Lot 3599 $n'=105 \times 10^4$			3" Gun 1925 Lot 2132-S		3" Gun 1918 $n' = 118 \times 10^4$	
Proj. Wt.	15.96	13.5	11.72	12.7	15.0	12.7	15
Charge	27.88 oz.	29.63 oz.	24.47 oz.	4.68 lbs.	4.61	3.99 lbs.	3.84 lbs.
Density of Loading	.584	.620	.512	.437	.431	.553	.531
Temperature °F	50°	50°	50°	50°	50°	50°	50°
P_{max}	31050	32520	21230	27170	27463	34870	30620
q	.0902	.0870	.0796	.1037	.1060	.0958	.0913
K'	.00394	.00411	.00405	.00376	.00357	.00432	.00382
Temperature °F	70°	70°	70°	70°	70°	70°	70°
P_{max}	33115	35017	21965	28295	28275	34050	32835
q	.0943	.0915	.0816	.1067	.1082	.0941	.0961
K'	.00412	.00433	.00415	.00387	.00364	.00424	.00402
Temperature °F	90°	90°	90°	90°	90°	90°	90°
P_{max}	33630	35640	21810	28570	27810	35720	33550
q	.0953	.0926	.0811	.1075	.1070	.0974	.0976
K'	.00417	.00438	.00412	.00390	.00361	.00439	.00408
Temperature °F	110°	110°	110°	110°	110°	110°	110°
P_{max}	36240	36920	22670	31260	31280	37620	36710
q	.1066	.1004	.0858	.1144	.1161	.1010	.1038
K'	.00466	.00475	.00436	.00415	.00401	.00455	.00434
Temperature °F	135°	135°	135°	135°	135°	135°	135°
P_{max}	39760	40190	23540	33480	33113	40190	38290
q	.1066	.1004	.0858	.1198	.1206	.1056	.1068
K'	.00466	.00475	.00436	.00435	.00406	.00476	.00447

Table II

Powder	a		P.e. of a	P.e. of b
Pyro	$.0170 \times 10^{-4}$	482	$.000353 \times 10^{-4}$	104
FNH	$.0160 \times 10^{-4}$	405	$.00191 \times 10^{-4}$	50
Pyro or FNH	$.0149 \times 10^{-4}$	415	$.00258 \times 10^{-4}$	75

Equation for K'

$$K' = \frac{.0149n' \times 10^{-4}}{415 - \Delta T}$$

Table III

Comparison of computed and exp. values of $\Delta V / \Delta T$

Gun	Type of Powder	Muzzle Vel. at 70° F	$\dfrac{\Delta V}{\Delta T}$ in ft/sec/deg F	
			Exp.	Computed
3" A.A. 1925	Pyro	2485	.91	.89
75 mm 1897	Pyro	1735	.60	.53
75 mm 1897	FNH	1805	.59	.86
75 mm 1897	Pyro	1097	.69	.53
155 mm How. 1918	Pyro	862	.70	.57
3" A.A. 1918	Pyro	2330	1.22	1.28

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A new equation for the specific rate of smokeless powder burning as a function of the temperature is developed. Constants in the equation are determined directly from the experimental data. Three tables are included. Table I is a summary of experimental data. Table II shows probable errors for two types of powder and for the case in which all the available data were used without regard to the kind of powder. Table III is a comparison between the computed and experimental values of $\Delta V/\Delta T$ for various guns, ΔT being the difference between T_0 and 21.1° C.

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